UK Calorimetry For ILC

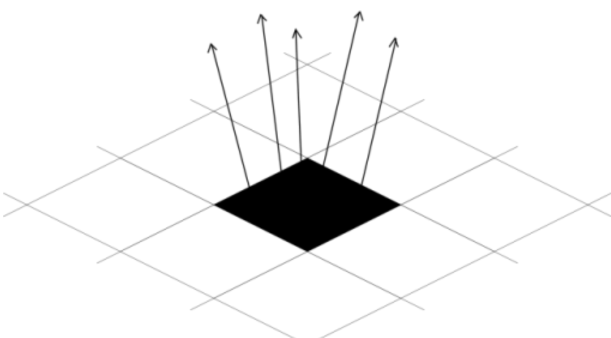
Alasdair Winter
University Of Birmingham

UK Calorimetry for LC

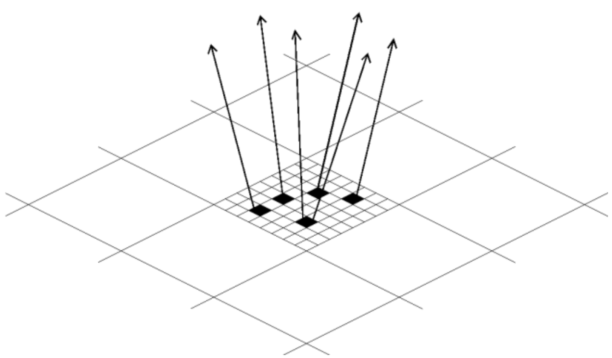
- Concentrating on niche UK interests given effort
- Most novel aspect is DECAL
- Reminder
  - (from 2005) digital calorimetry (CALICE)
  - Followed by SPIDER
  - Arachnid (generic detector and ALICE ITS)
  - Main sensors for calorimetry were TPAC (engineering run, sensors 28k pixels, 50x50μm^2)
  - CHERWELL (MPW, tracking and vertexing, and some DECAL components)
- CMOS sensors, epitaxial layer thickness ~10-20 μm
  - CHERWELL, 4T structures studied: in-pixel structure structures, correlated double sampling (CDS), improved S/N, low power (~10W/pixel)
  - DECAL parts not characterised so far

DECAL Concept - Reminder

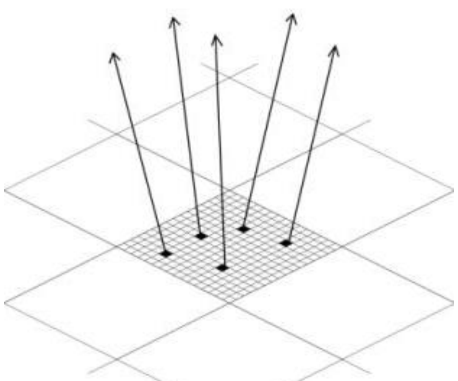
- Concept, swap ~0.5x0.5 cm^2 Si pads with small pixels ("Small" := at most one particle/pixel,1-bit ADC/pixel)
- How small to avoid saturation/non-linearity?
  - EM shower core density at 500GeV is ~100/mm^2
  - Pixels must be<$100\times100\mu m^2$
    - Used baseline $50\times50\mu m^2$
  - Gives ~10^{12} pixels for ECAL – "Tera-pixel APS"
  - Mandatory to integrate electronics on sensor



AECAL



DECAL $N_{pixels}<N_{particles}$



DECAL $N_{pixels}=N_{particles}$

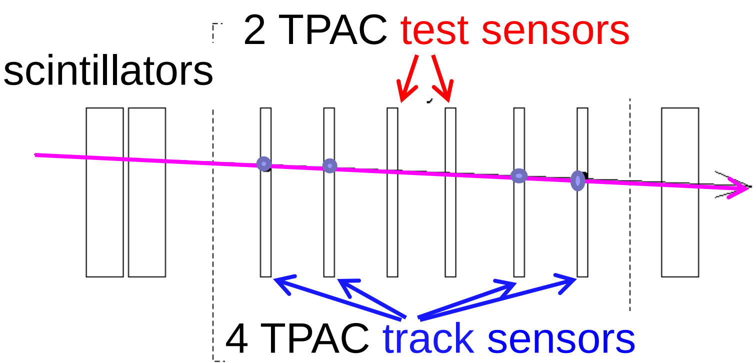
DECAL: CMOS MAPS for Linear Collider

- Mature, high volume industrial devices: no proprietary processes → reduced costs
- Low(-ish) power, depends on duty cycle
- Low material budget, can be very thin
- Radiation hard (few >Mrad)
  - OK for ILC ECAL, but not for other applications, e.g. HL-LHC, FCC(h)
- Very granular (pixels ~10um)

New features developed for LC

- TPAC et al. (digital ECAL)
- Deep p-well implant/InMAPS process
  - Makes MAPS viable
  - Improved charge collection efficiency
- High resistivity/HV epitaxial layers
  - Further charge collection and radiation hardness improvements

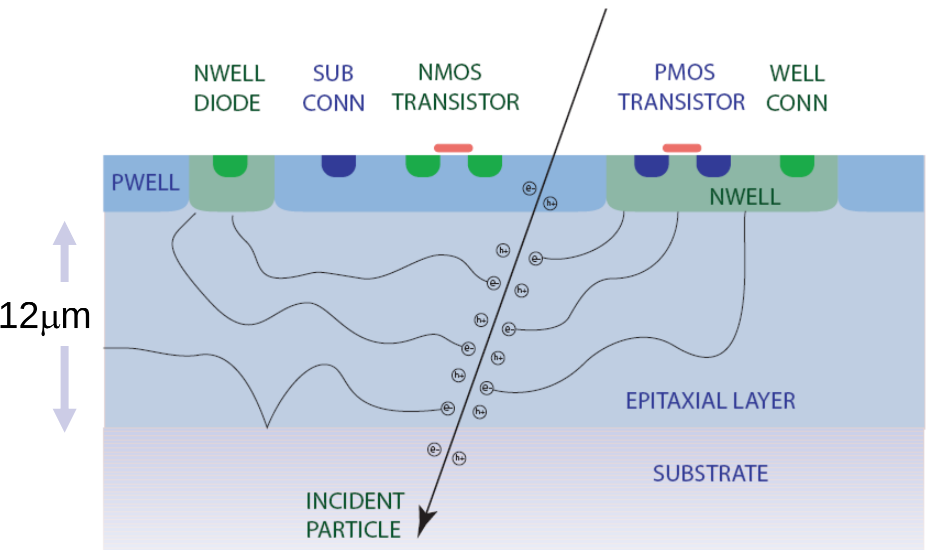
MAPS, MIP Efficiency



Project tracks to individual test sensors

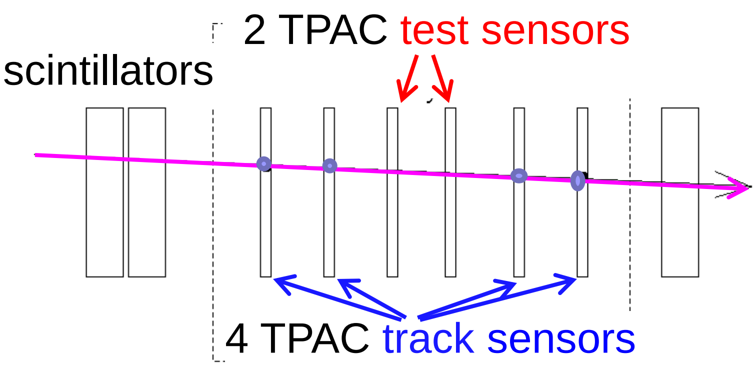
Check for sensor hits as function of track (x,y) position relative to pixel centre

Determine efficiency by fitting distribution



- Efficiency for 4 sensor variants, from CERN (Aug.'09, 120 GeV π) and DESY (Mar.'10, 1-5 GeV e^-) testbeams
- Standard CMOS sensors have low efficiency due to signal absorption by circuit elements
- Deep p-well (INMAPS) reduces signal absorption, raises efficiency by factor ~5
- (12µm) high-resistivity epitaxial layer raises efficiency by *further* factor *~x2*

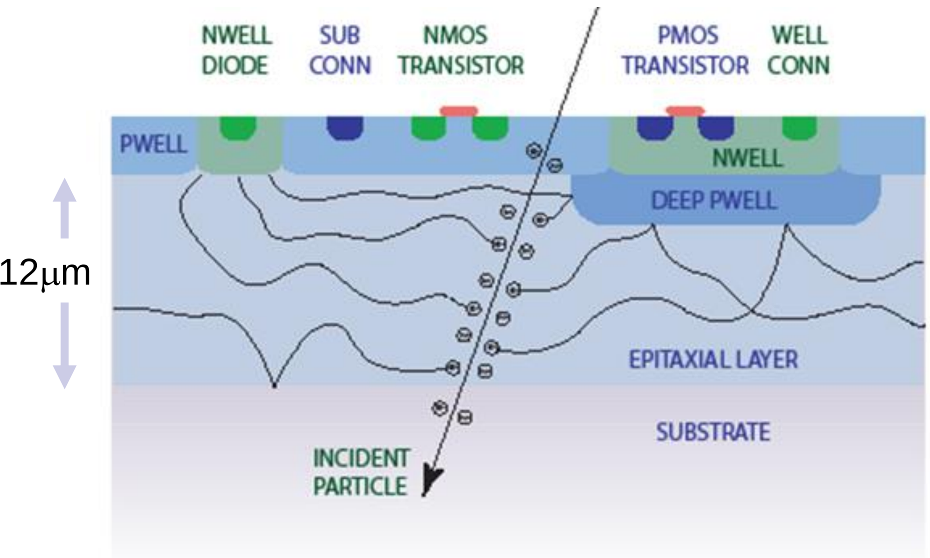
MAPS, MIP Efficiency



Project tracks to individual test sensors

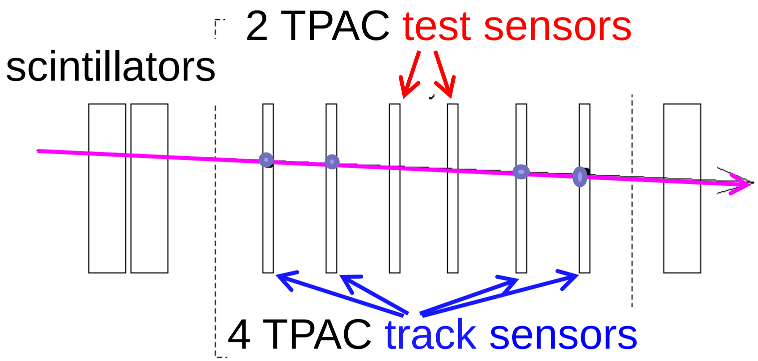
Check for sensor hits as function of track (x,y) position relative to pixel centre

Determine efficiency by fitting distribution



- Efficiency for 4 sensor variants, from CERN (Aug.'09, 120 GeV π) and DESY (Mar.'10, 1-5 GeV e^-) testbeams
- Standard CMOS sensors have low efficiency due to signal absorption by circuit elements
- Deep p-well (INMAPS) reduces signal absorption, raises efficiency by factor ~5
- (12μm) high-resistivity epitaxial layer raises efficiency by *further* factor ~x2

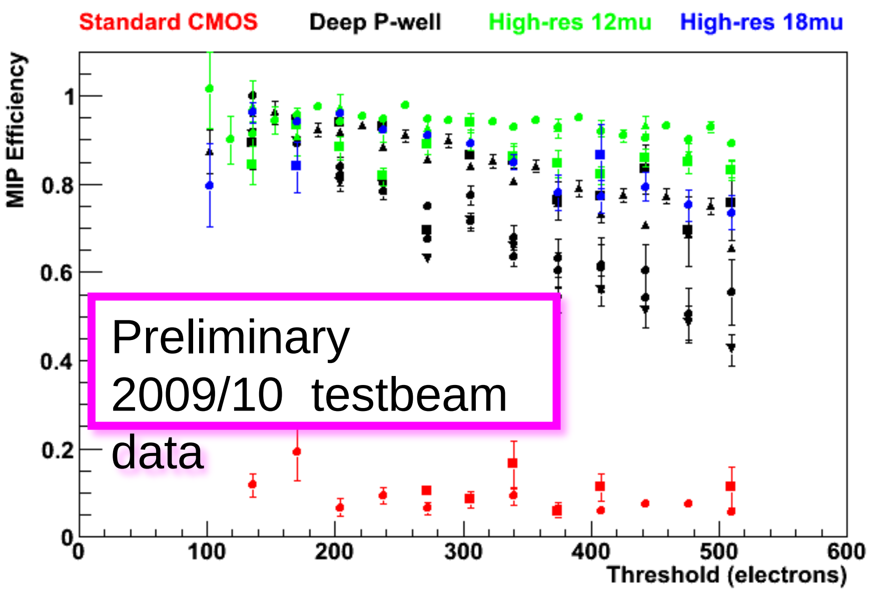
MAPS, MIP Efficiency



Project tracks to individual test sensors

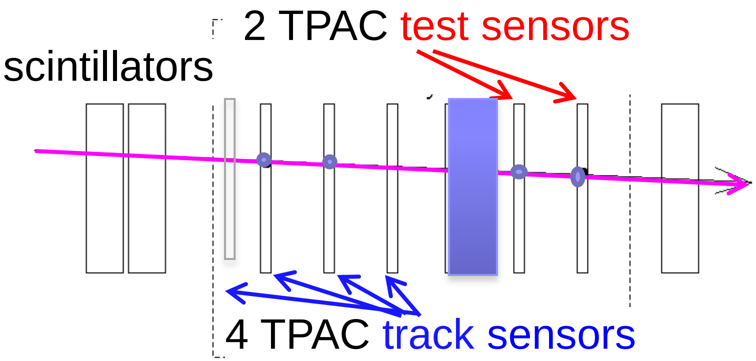
Check for sensor hits as function of track (x,y) position relative to pixel centre

Determine efficiency by fitting distribution



- Efficiency for 4 sensor variants, from CERN (Aug.'09, 120 GeV π) and DESY (Mar.'10, 1-5 GeV e^-) testbeams
- Standard CMOS sensors have low efficiency due to signal absorption by circuit elements
- Deep p-well (INMAPS) reduces signal absorption, raises efficiency by factor ~5
- (12μm) high-resistivity epitaxial layer raises efficiency by *further* factor *~x2*

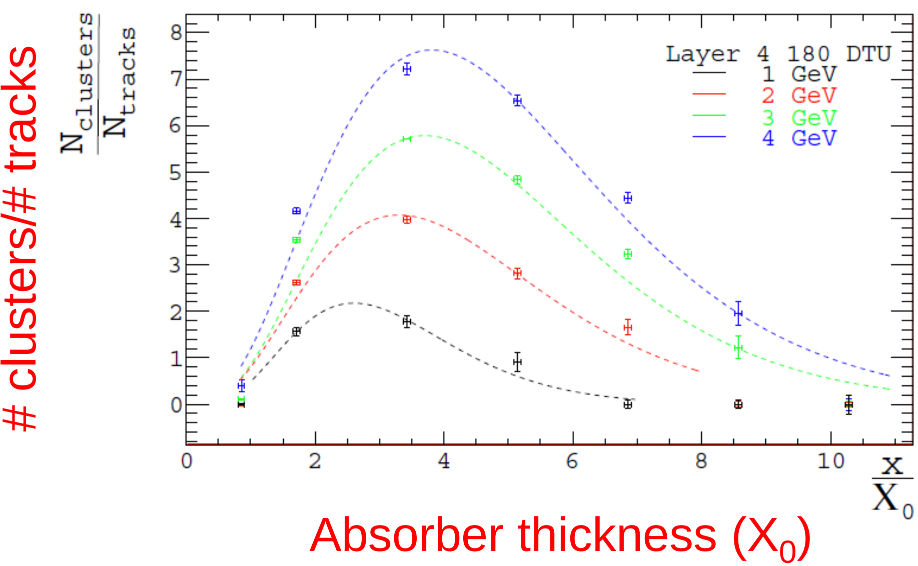
MAPS for DECAL, (~)Shower Profile



Project tracks to individual test sensors

Vary depth of absorber thickness, study downstream hit multiplicity

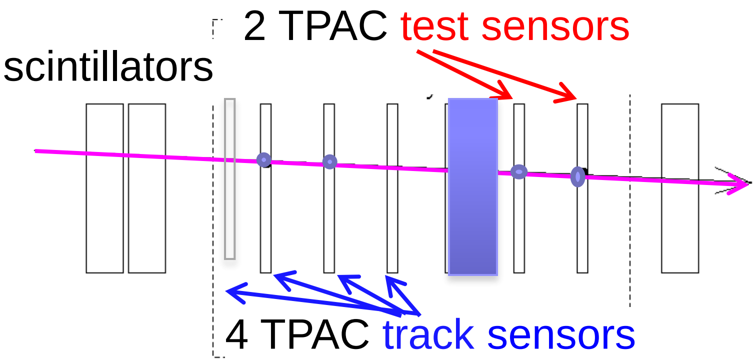
Purely to cut cost – not ideal



- Study TPAC sensors as "calorimeter" layer
- Peak of sensor activity vs. depth of material

- Single sensor study of EM shower response
- Electron beam shows expected log behaviour
- (NB: single sensor transverse size)

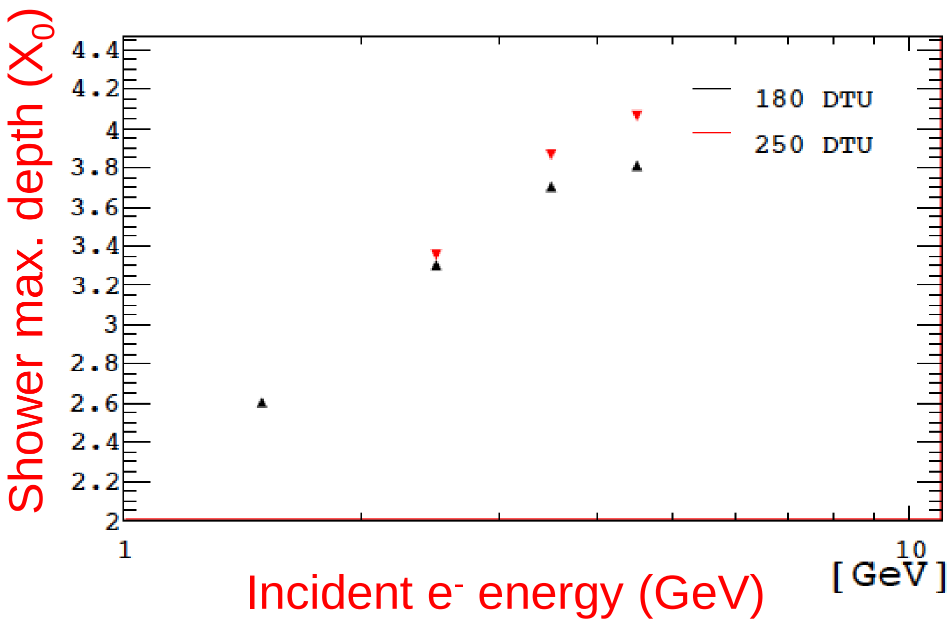
MAPS for DECAL, (~)Shower Profile



Project tracks to individual test sensors

Vary depth of absorber thickness, study downstream hit multiplicity

Purely to cut cost – not ideal

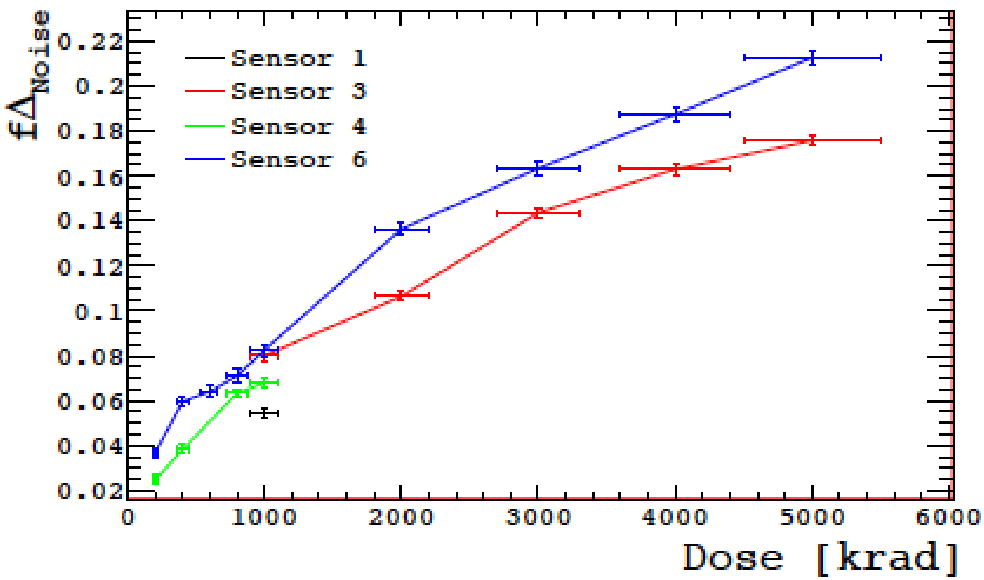


- Now (Bham, PPD, Sussex) using CHERWELL sensor to find show stoppers for DECAL
- Power consumption (→ 1% duty cycle “no harm” tests)
- Pixel ganging (exploit tracker technology)
- Future (-- “ --), investigating rad hard MAPS for DECAL and tracking (higher intensity hadron colliders + LC)

Radiation hardness testing

- Potential use of TPAC sensor technology in high radiation environments such as tracking and vertex systems
- Need to understand sensor's response/tolerance
- Multiple sensors tested, 50 keVγ
- Sensors held at 0 V and 1.8 V
- Exposures between 0.2-5.0 Mrad
- Mean noise and pedestal of the pixels tested after each dose
- Conclusion: rad. Hard enough for use in ILD (CLIC ILD or ILC ILD)

Fractional increase in noise, Non-biased sensors (@60rad/s)



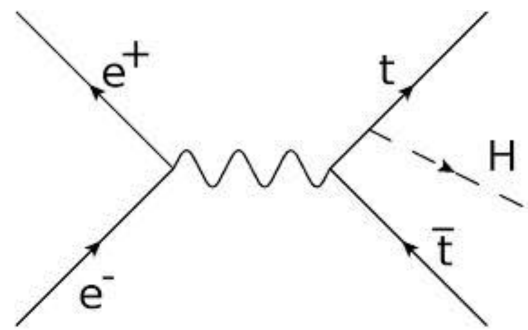
Acceptable noise increase to ~5 MRad

T Price *et al, First radiation hardness results of the TeraPixel Active Calorimeter (TPAC) sensor*, 2013 *JINST* 8 P01007,doi:10.1088/1748-0221/8/01/P01007

Pre-2015 studies

- Full Mokka, DBD vintage
- Compare SiECAL with DECAL in ttH study
- Multi-jet performance
- Detector model ILD_01_v02
- Only parameters changed were
  - Cell sizes reduced to 50x50μm^2
  - Sensitive epi thickness to 12μm (as in TPAC sensor)
  - Digital readout turned on in PandoraPFA
- Minimal change in performance
  - Individual quantities and “bottom line” for ttH analysis
  - All details in Tony Price thesis and papers:

T. Price, N. Watson, T. Tanabe, and V. Martin, *Measurement of the top Yukawa coupling at sqrt(s)=1 TeV using the ILD detector* LC-REP-2013-004, http://www-flc.desy.de/lcnotes/notes/LC-REP-2013-004.pdf



- Study semileptonic channel
- 6 hadronic jets, 1 charged lepton, neutrino
- Good test of PFA impact of ECAL
- MVA-based removal of ttZ, tt, ttbb backgrounds

T. Price, P. Roloff, J. Strube and T. Tanabe, *Full simulation study of the top Yukawa coupling at the ILC at sqrt(s) = 1 TeV*, Eur. Phys. J. C (2015) 75:309

Pre-2015 studies

- Full Mokka, DBD vintage
- Compare SiECAL with DECAL in ttH study
- Multi-jet performance
- Detector model ILD_01_v02
- Only parameters changed were
  - Cell sizes reduced to 50x50μm^2
  - Sensitive epi thickness to 12μm (as in TPAC sensor)
  - Digital readout turned on in PandoraPFA
- Minimal change in performance
  - Individual quantities and “bottom line” for ttH analysis
  - All details in Tony Price thesis (and papers:

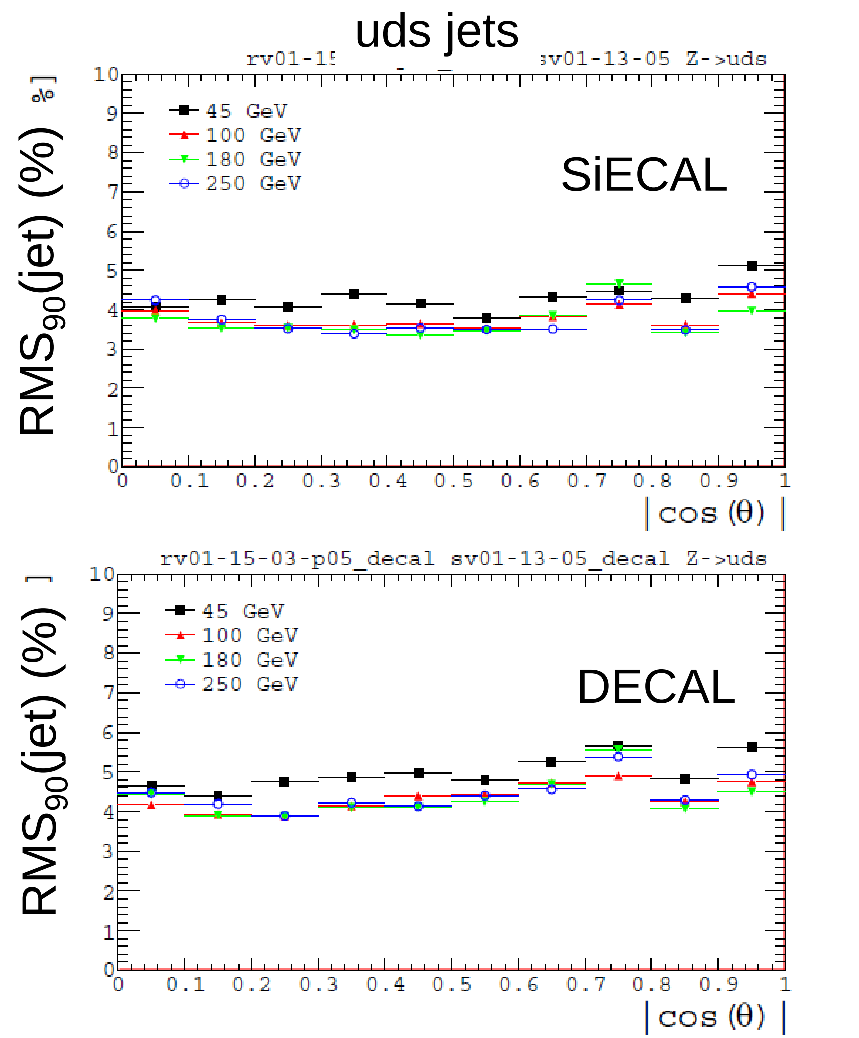


Figure 6.4: Jet energy resolution ($\frac{RMS_{90}}{E_{90}}$) as a function of angle from the beamline for the Z→uds events at centre of mass energies of 91, 250, 360, and 500 GeV for the DECAL using iLCSoft v01-13-05_decal and reconstruction v01-15-03-p05_decal.

For Calice

- Birmingham (Nigel, Alasdair Winter, +), Sussex (Fabrizio Salvatore, Tom Coates, +), RAL,+
- Concentrate on niche area where we could make some impact
- Opportunity to clarify (or abandon) future of DECAL

- Thomas Peitzmann’s group (Utrecht/Alice), joined CALICE very recently
- Genuinely complementary activities – but some competition

- UK groups will investigate “show-stoppers” for DECAL principle
- Assume no sensor we have at present would be used after 2016
- Modest ongoing studies of DECAL in specific areas
  - Power consumption (duty cycle - “no harm” tests)
  - Pixel ganging (exploit tracker technology)
  - Preparing to characterise DECAL parts of CHERWELL sensor

- We (Bham, RAL, Sussex) are now working with ATLAS group to develop rad-hard MAPS for multiple applications including DECAL

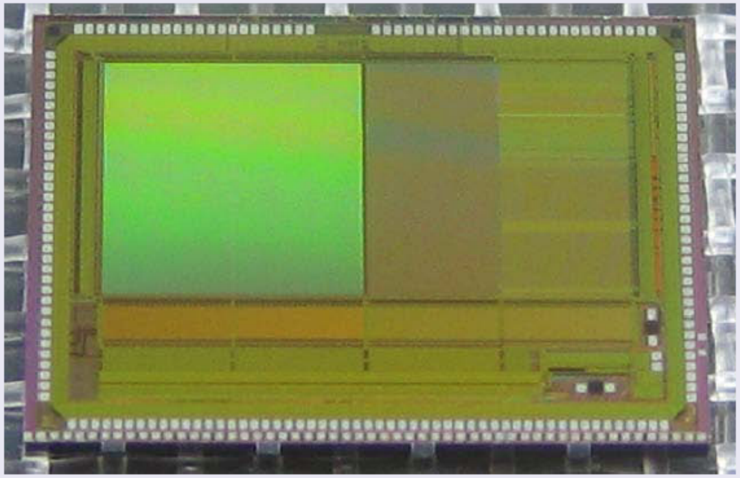
Cherwell Overview

4 test structures on 3 different epitaxial layers

1. DECAL 25: 48×96 $25\,\mu m$ pixels with 2×2 summing.
2. DECAL 50: 24×48 $50\,\mu m$ pixels.
3. Reference: 48×96 $25\,\mu m$ pixels with ADC at column base.
4. Strixel: 48×96 $25\,\mu m$ pixels with ADC embedded in pixel.

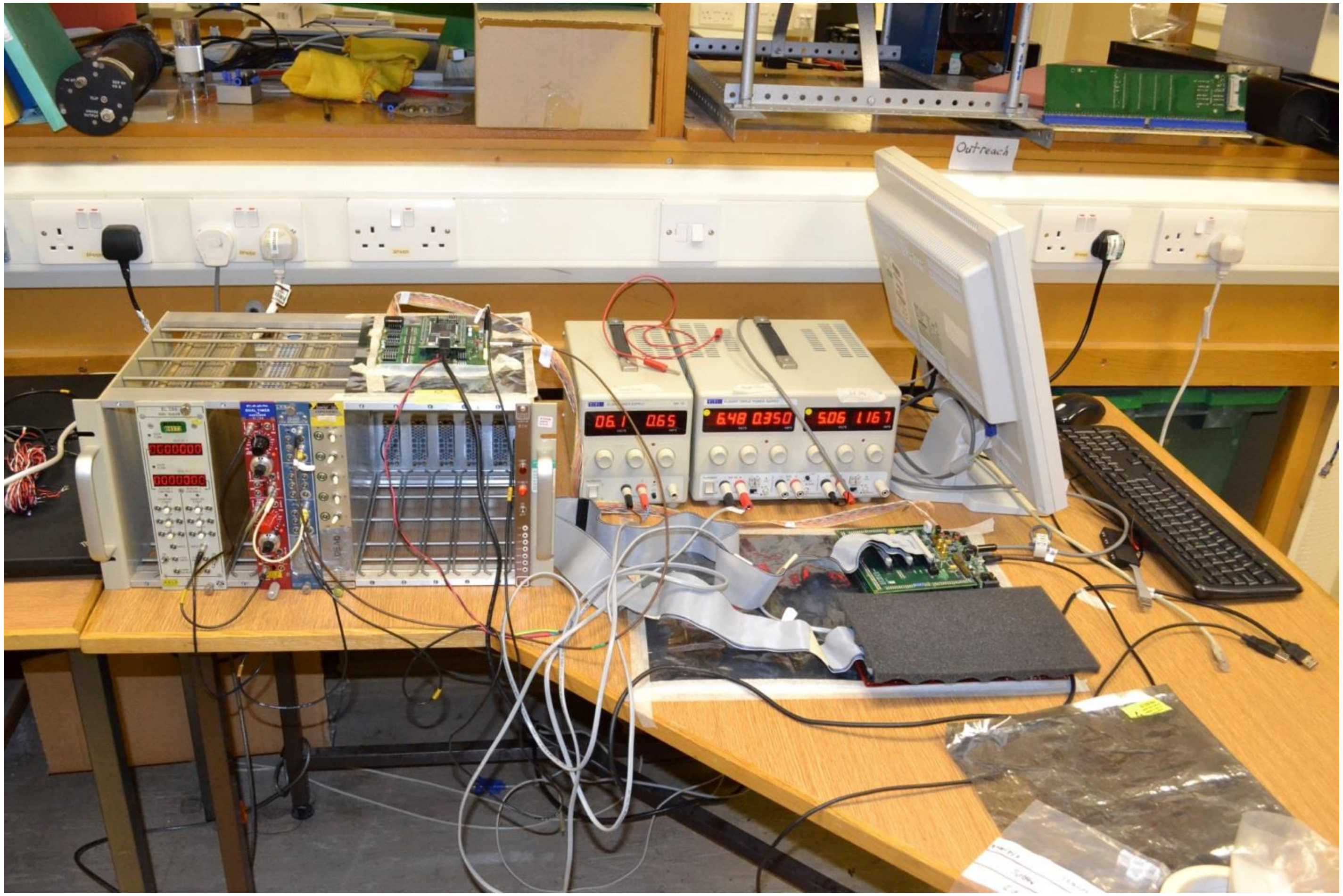
Additional features (in most variants)

- $0.5 \times 0.5\,\mathrm{cm}^2$, digital readout.
- $0.18\,\mu m$ process, 4T structures, CDS.
- 12-bit ADC, rolling shutter, stores 10 time slices.
- Global shutter for DECAL.
- Supports power pulsing.



See Fergus Wilson's talk, ECFA LC 2013, DESY, for generic MAPS/silicon R&D in UK

Test stand at Bham



Cooling and power

- Cooling for the ECAL is a general issue
- Compared to analog pad ECAL
  - Factor 10^3-10^4 more Channels
  - Factor ~10 more power
- Power Savings due to duty cycle (1%)
- Target Value for existing ECAL ASICS
  - 4 μW/mm2
- Last measured (years ago) consumption of MAPS ECAL:
  - 40 μW/mm2 depending on pixel architecture
  - TPAC1 not optimized at all for power consumption
- Advantage: Heat load is spread evenly
- Aim: characterise for noise/source/laser
- Study impact of variable duty cycle (firmware controlled), how close to 1% can we go?
- Some difficulties with firmware, work in progress from designer at DL
- So…

ILD optimisation

- Following completion of $e^+e^- \rightarrow \nu\nu H(H\rightarrow WW^*, WW^*\rightarrow qql\nu)$ for CLIC Higgs paper (not detector study)
- Use ILD to test DECAL design, for new sensors
  - Explore potential gain from very high granularity of MAPS
  - Previously shown no performance loss for hadronic jets relative to SiW
  - Next, use $e^+e^-\rightarrow ZH$ ($H\rightarrow\tau^+\tau^-$), and $\tau^-\rightarrow h^-\pi^0\nu_\tau$ to test benefit of pixels ~50μm for PFA
  - Study for whole ECAL or preshower detector
  - Use Mokka, ILD-01-v05, ScEcal04 in ILCSoft-17-07
  - Geometry of ECAL udpated w.r.t. previous studies
  - New Pandora, with improved tools to determine calibration parameters based on test samples of photons, K_L and muons
- Work will continue in parallel with other studies for DECAL (not for ILC)

Rad-hard maps proposal

- New opportunity
  - Motivated by FCC(h), HL-LHC, ILC/CLIC
  - Fully monolithic device that is rad hard has many potential applications
- Includes ILC, even though we don’t need rad-hard parts, new sensor line
  - Funding agreed Dec. 2015

Development towards a Reconfigurable Monolithic Active Pixel Sensor in Radiation-hard Technology for Outer Tracking and Digital Electromagnetic Calorimetry

P.P. Allport[1], D. Das[2], L. Gonella[1*], S.J. Head[1], K. Nikolopoulos[1], S. McMahon[2], P.R. Newman[1],

P. Phillips[2], F. Salvatore[3], R. Turchetta[2], G. Villani[2], N.K. Watson[1], F. Wilson[2], Z. Zhang[2]

1) The University of Birmingham

2) Rutherford Appleton Laboratory, STFC

3) The University of Sussex

Abstract

Monolithic Active Pixel Sensor (MAPS) technologies have been deployed as a vertexing detector in particle physics at RHIC [1] and have been proposed for a number of projects including ALICE and, in particular, for use at the ILC [2]. Their thin sensing region allows applications providing very low multiple scattering, vital for the tracking layers closest to the interaction if secondary vertices are to be identified with high efficiency. Because they employ standard CMOS technologies used for high volume manufacturing, their production costs can be much lower than standard planar silicon. Such affordability and large production capability has led to concepts based on several thousand m^2 of such technology being considered for the sampling layers in calorimeters at future colliders. Furthermore, the digital read-out technology proposed for the calorimeter could also be employed for outer tracking and pre-shower detectors, giving unprecedented particle flow capabilities

Originally, the use of conventional CMOS sensors for particle physics was limited, both in terms of signal speed and radiation hardness, due to the charge collection being through diffusion. However, this proposal exploits new, much faster and radiation-hard technologies for which RAL has been in the vanguard of developments, together with digital calorimeter detector designs for the ILC where first prototypes already exist [3]. This proposal is to build a demonstrator sensor targeting HL-LHC and FCC-hh radiation levels that has the potential to also meet the extreme data rate requirements at such facilities.

The proposal builds on established areas of UK expertise in digital calorimetry, outer tracking, MAPS development and radiation-hard sensor R&D to position the UK to take a leading role in the development of detectors for future high rate, high radiation experimental environments such as those at proposed future hadron colliders.

Pre-project start, planning DAQ Dev./ Device Evaluation

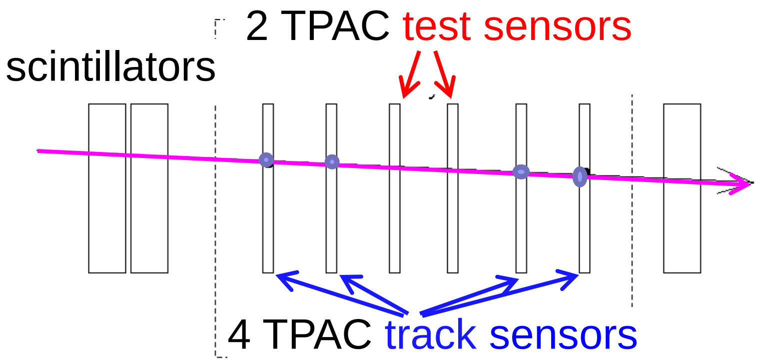
- DAQ to be adapted from ATLAS HR/HV-CMOS
  - Interfaces to PC/root
  - Planning in advance of sensor arrival essential
  - Only two year funding, starts 1 June 2016
- Detailed characterisations anticipated, different requirements.
  - Number of test stands to produce?
  - Adaptations for specific tests, or to use existing sensor before our own arrive?
    - e.g. for radiation environment (mezzanine etc.), mechanical constraints,
- Irradiation
  - 28 MeV protons (bulk and electronics) - Birmingham
  - X-rays, ^{60}Co γ (electronics only)
- Test beam
  - Incl. EUDET telescope (but implication for DAQ choice)
- Gain characterisation
  - ^{55}Fe source (RAL)
  - ^{90}Sr (Bham) – higher intensity
- Laser
  - Various λ (few hundred → 1032 nm), so front and back illumination possible - RAL

Conclusions

- Rejoined efforts on CALICE, concentrate on niche areas of UK expertise, incl. DECAL
- New group (Utrecht/ALICE) in CALICE also working on DECAL/MAPS now
  - Complementary to the UK work – different sensor line (LHC funding)
- Simulation studies (ILD) to explore benefit of ultra-high granularity ECAL in progress
- DECAL hardware project has restarted
  - Use existing sensors (CHERWELL) with DECAL functionality to address specific items of need
    - Power consumption (duty cycle, “no harm” tests)
    - Pixel ganging (exploit tracker technology)
  - Aim to look for show-stoppers
- Opportunity to work with ATLAS et al. on rad-hard MAPS for calorimetry
- Approved Dec. 2015, project start 1 Jun 2016
- UK groups are being revived ☺

Backup slides

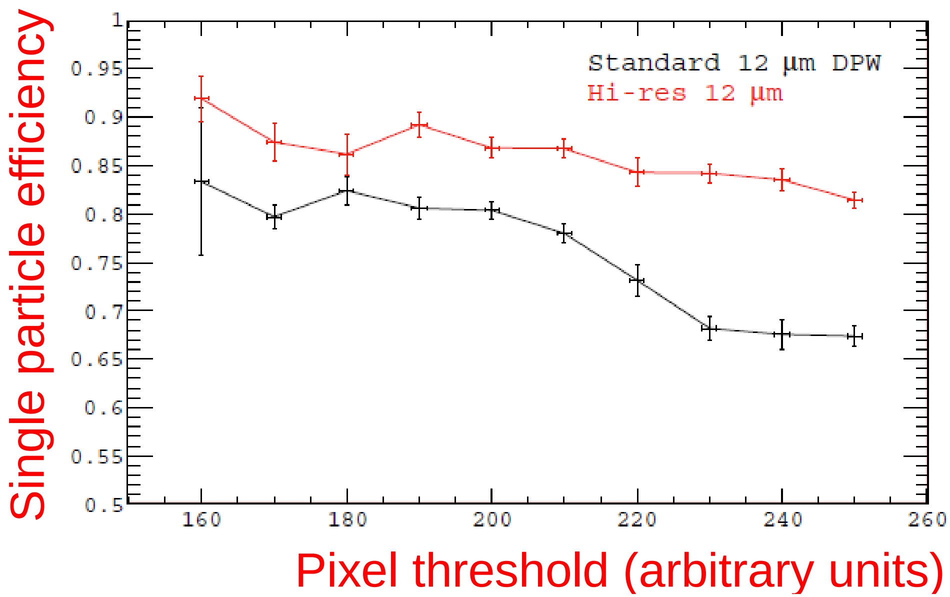
TPAC Sensor beam tests, MIP Efficiency



Project tracks to individual test sensors

Check for sensor hits as function of track (x,y) position relative to pixel centre

Determine efficiency by fitting distribution



[From T.Price, PhD thesis, Aug. 2013, Univ. Birmingham]

- Efficiency for 4 sensor variants, from CERN (Aug.'09, 120 GeV π) and DESY (Mar.'10, 1-5 GeV e^-) testbeams
- Standard CMOS sensors have low efficiency due to signal absorption by circuit elements
- Deep p-well (INMAPS) reduced signal absorption, raises efficiency by factor ~5
- (12μm) high-resistivity epitaxial layer raises efficiency by *further* factor ~x2

Further reading (primarily for calorimetry and TPAC aspects)

- Price, Tony (2013) *Digital calorimetry for future e+e− linear colliders and their impact on the precision measurement of the top Higgs Yukawa coupling.* Ph.D. thesis, University of Birmingham
- T Price *et al, First radiation hardness results of the TeraPixel Active Calorimeter (TPAC) sensor*, 2013 *JINST* 8 P01007,doi:10.1088/1748-0221/8/01/P01007
- M.Stanitzki, *Advanced monolithic active pixel sensors for tracking, vertexing and calorimetry with full CMOS capability,* **Nucl.Instrum.Meth. A650 (2011) 178-183**
- P.Dauncey et al., *Performance of CMOS sensors for a digital electromagnetic calorimeter,* ICHEP 2010, Paris, **PoS ICHEP2010 (2010) 502**
- N.K.Watson et al., *A MAPS-based readout of an electromagnetic calorimeter for the ILC,* **J.Phys.Conf.Ser. 110 (2008) 092035**
- J.A. Ballin et al., *Design and performance of a CMOS study sensor for a binary readout electromagnetic calorimeter*, 2011 *JINST* 6 P05009,doi:10.1088/1748-0221/6/05/P05009
- J.A.Ballin et al., *Monolithic Active Pixel Sensors (MAPS) in a quadruple well technology for nearly 100% fill factor and full CMOS pixels, Sensors* **2008**, *8*(9), 5336-5351; doi:10.3390/s8095336

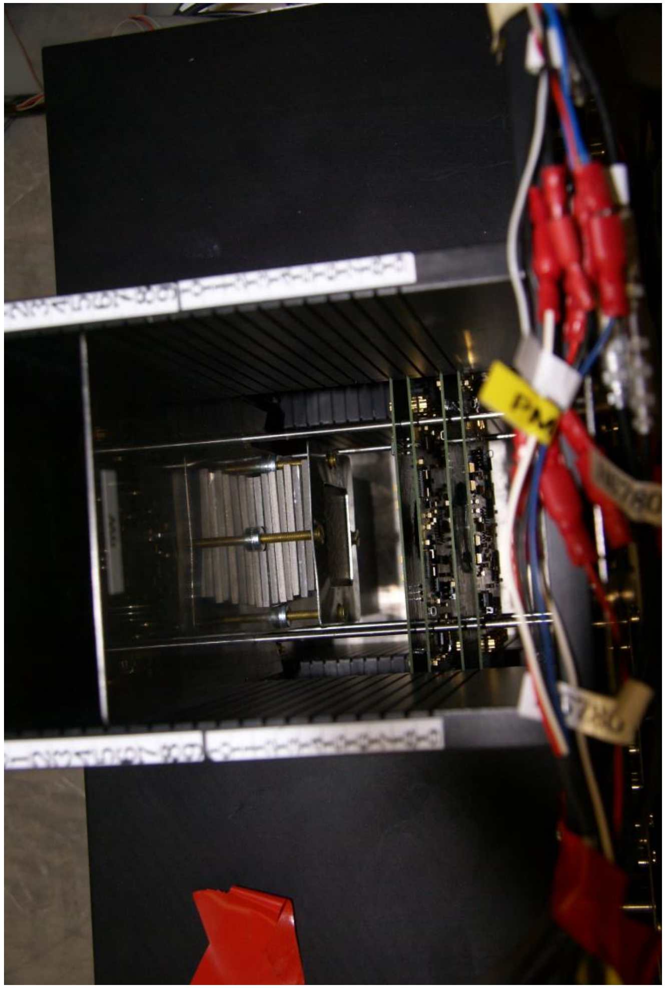
- Plus many other conference talks, ILC, TIPP, etc., see
  - https://www.spider.ac.uk/pages/viewpage.action?pageId=1114156
  - http://hepwww.rl.ac.uk/calice/Conference-planer.html

DAQ Requirements

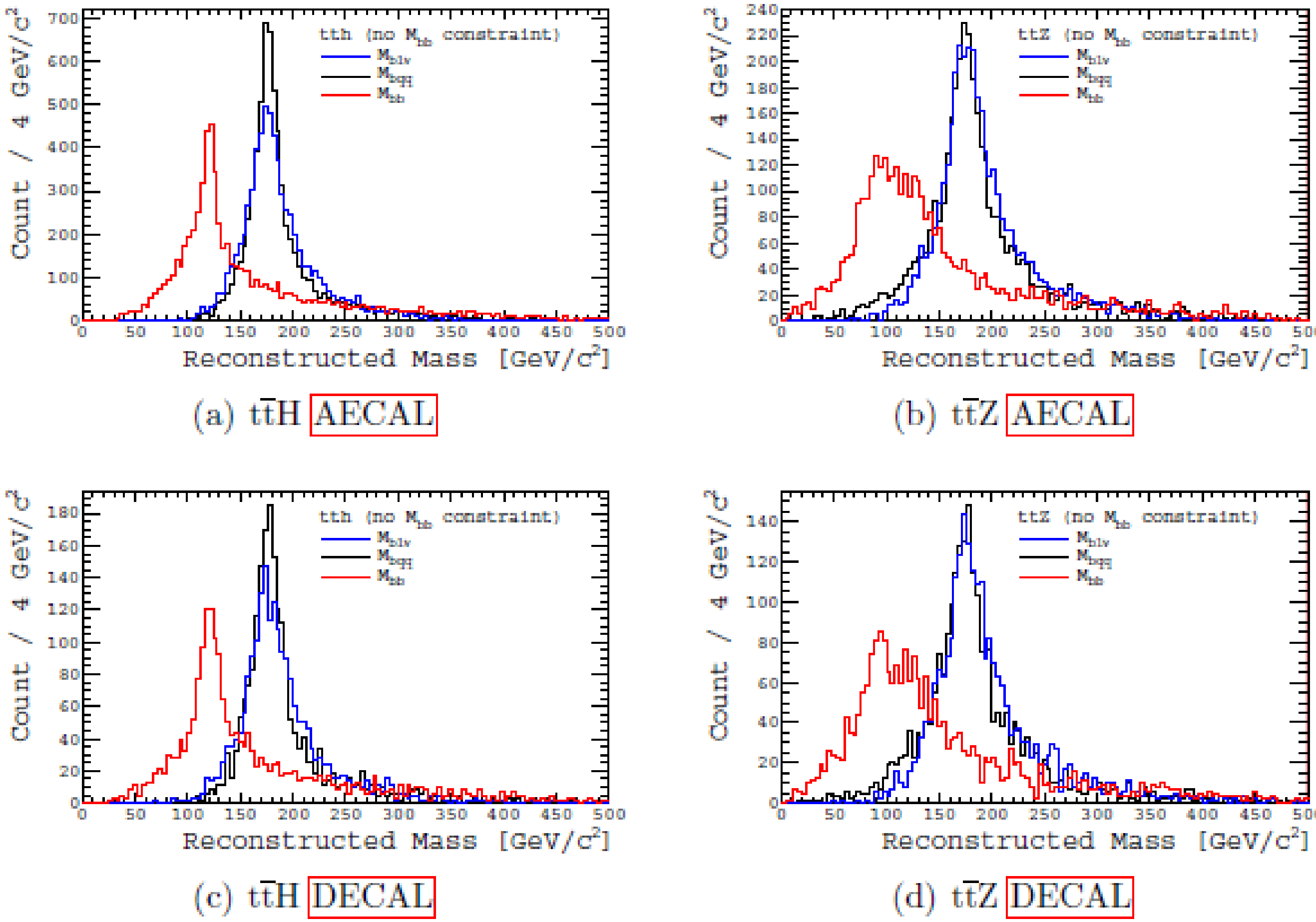
- $O(10^{12})$ channels are a lot ...
- Physics rate is not the limiting factor
- Beam background and Noise will dominate
- Assuming ~2600 bunches and a (pessimistic) full 32 bits/hit
  - 10^6 Noise hits per bunch
  - ~O(1000) Hits from Beam background per bunch (estimated from GuineaPIG)
- Per bunch train
  - ~80 Gigabit / 10 Gigabyte
  - Readout speed required 400 Gigabit/s
  - Comparison: CDF SVX-II did 144 Gigabit/s

Characterisations for TPAC

- Historical context,what we did last time…
- Beam tests:
  - CERN 20-120 GeV pions
  - DESY 1-5 GeV electrons
- Radiation hardness
- Noise/Gain ^{55}Fe



More figures of merit



(a) $t\bar{t}H$ AECAL (b) $t\bar{t}Z$ AECAL

(c) $t\bar{t}H$ DECAL (d) $t\bar{t}Z$ DECAL

Figure 6.12: The reconstructed masses for the two top quarks and $b\bar{b}$ pair when the Higgs mass constraint is removed for the $t\bar{t}H$ and $t\bar{t}Z$ channels when using the AECAL (top) and DECAL (bottom).

LCUK, 2016

More figures of merit

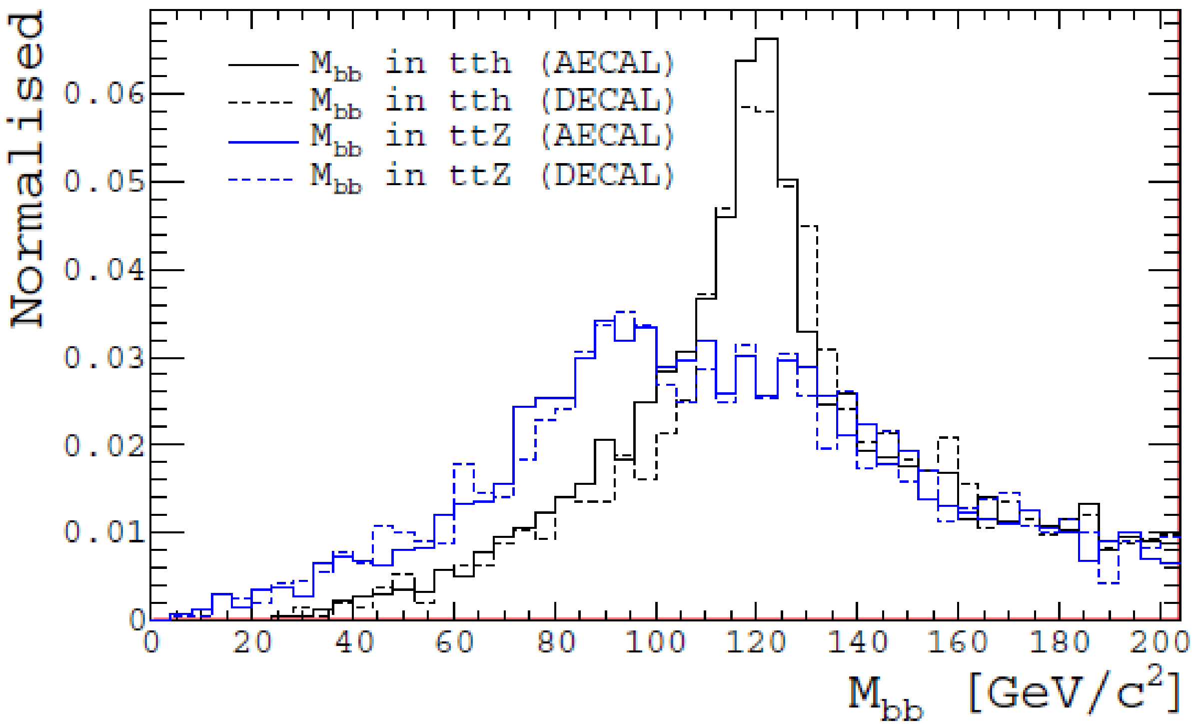


Figure 6.13: The reconstructed mass of the $b\bar{b}$ system when the Higgs mass constraint is removed for the $t\bar{t}H$ (black) and $t\bar{t}Z$ (blue) samples for the AECAL (solid lines) and DECAL (dashed lines).

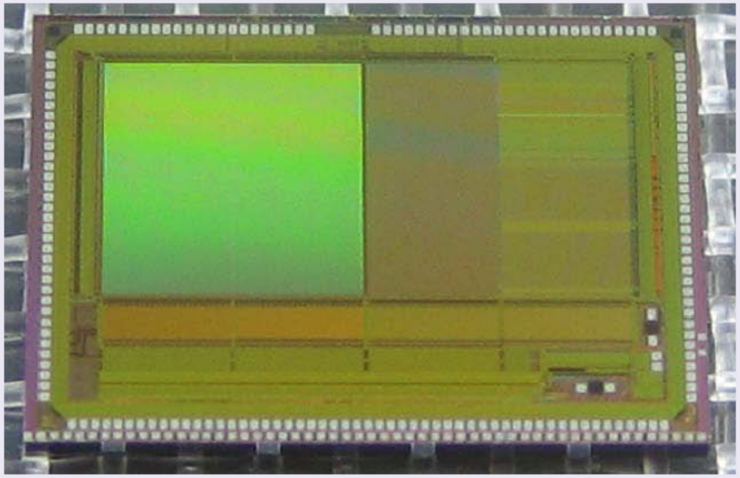
Cherwell Overview

4 test structures on 3 different epitaxial layers

1. DECAL 25: 48×96 25 μm pixels with 2×2 summing.
2. DECAL 50: 24×48 50 μm pixels.
3. Reference: 48×96 25 μm pixels with ADC at column base.
4. Strixel: 48×96 25 μm pixels with ADC embedded in pixel.

Additional features (in most variants)

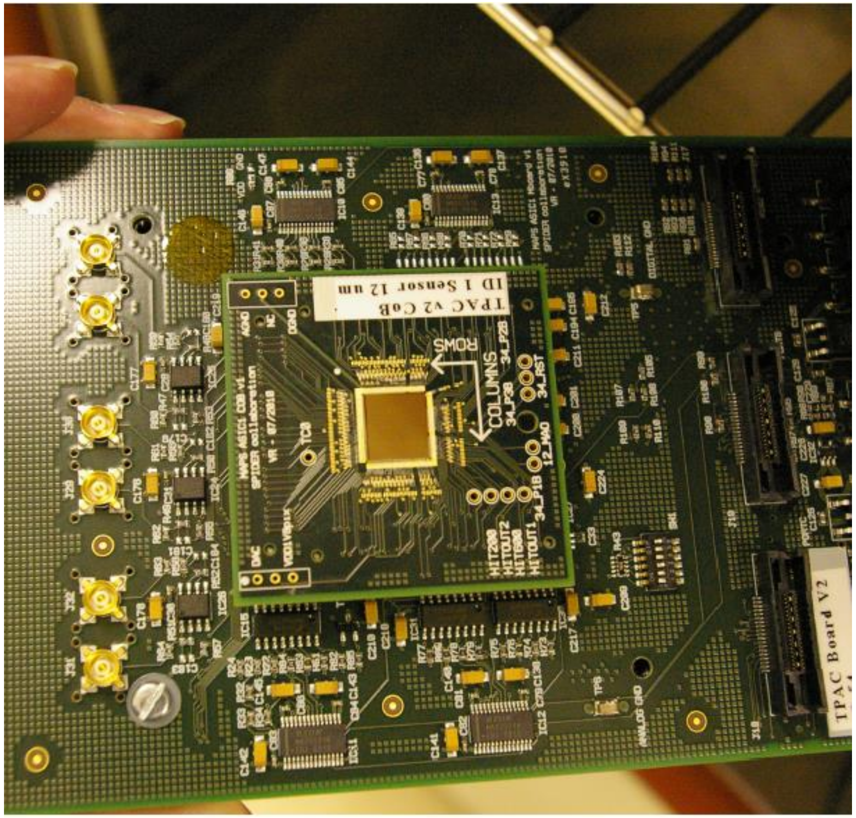
- $0.5 \times 0.5\,\mathrm{cm}^2$, digital readout.
- 0.18 μm process, 4T structures, CDS.
- 12-bit ADC, rolling shutter, stores 10 time slices.
- Global shutter for DECAL.
- Supports power pulsing.



See Fergus Wilson's talk, ECFA LC 2013, DESY, for generic MAPS/silicon R&D in UK

Radiation hardness testing

- Potential use of TPAC sensor technology in high radiation environments such as tracking and vertex systems
- Need to understand sensor's response/tolerance
- Multiple sensors irradiated, 50 keVγ
- Sensors held at 0 V and 1.8 V
- Exposures between 0.2-5.0 Mrad
- Mean noise and pedestal of the pixels tested after each dose
- Conclusion: rad. Hard enough for use in ILD (CLIC ILD or ILC ILD)



T Price *et al, First radiation hardness results of the TeraPixel Active Calorimeter (TPAC) sensor*, 2013 *JINST* 8 P01007,doi:10.1088/1748-0221/8/01/P01007

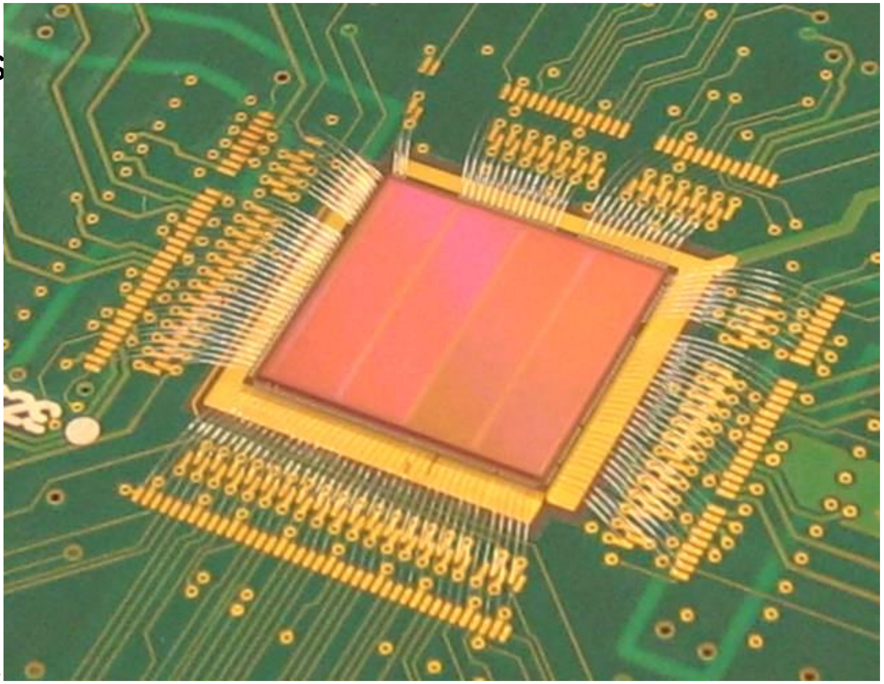
Radiation hardness testing

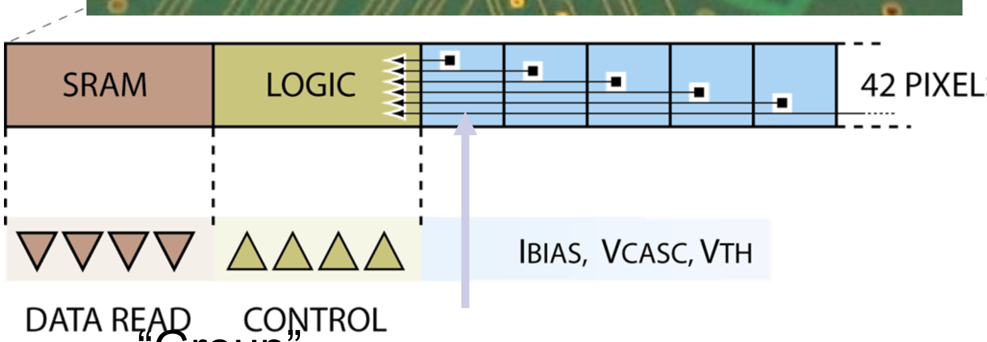
- Potential use of TPAC sensor technology in high radiation environments such as tracking and vertex systems
- Need to understand sensor's response/tolerance
- Multiple sensors irradiated, 50 keVγ
- Sensors held at 0 V and 1.8 V
- Exposures between 0.2-5.0 Mrad
- Mean noise and pedestal of the pixels tested after each dose
- Conclusion: rad. Hard enough for use in ILD (CLIC ILD or ILC ILD)

T Price *et al, First radiation hardness results of the TeraPixel Active Calorimeter (TPAC) sensor*, 2013 *JINST* 8 P01007,doi:10.1088/1748-0221/8/01/P01007

TPAC Overview

- Test device, ~1x1cm^2, 8.2 million transistors
- 28224 pixels; 50 μm pitch
- Pixel: 4 diodes, Q-preamp, mask+trim
- Sensitive area 79.4mm^2; charge diffusion
- Four columns of logic+SRAM
  - Logic columns serve 42 pixel “region”
  - Hit locations & (13 bit) timestamps
  - Local SRAM
  - 11% deadspace for readout/logic
- Data readout
  - Slow (<5 MHz) – train buffer
  - Current sense amplifiers
  - Column multiplex
  - 30 bit parallel data output





“Group”
(region=7 groups of 6 pixels)